Fiber optic sensor for industrial process measurement and control

Peter DeBarber

Tom Jenkins

MetroLaser, Inc.

2572 White Road, Irvine, CA 92614-6236
Tel: (949) 553-0688 Fax: (949) 553-0495

www.metrolaserinc.com
email: general@metrolaserinc.com

Project Overview

- **Project description**
  - SBIR: ϕ_1 ~1 y feasibility study; ϕ_2 ~2 y prototype development and testing effort; ϕ_3 ~1 y real-world demo system
- **Objectives**
  - Design and build the system - completed
  - Calibrate and test the system in a laboratory - completed
  - Integrate the system into a practical combustor - completed
  - Demonstrate the system in real-world conditions
- **Overall goal**
  - To produce a prototype Tunable Diode Laser Absorption Spectroscopy (TDLAS) instrument for practical use in combustion applications

Presentation Overview

- **Technical merit**
  - Thermometry example
- **Approach**
  - Scanned wavelength absorption spectroscopy using near IR diode lasers
- **Background**
- **Technical progress and outlook**
- **Phase II prototype tests**
  - Combustion chemical vapor deposition (CCVD) torch
  - Staged low-NOx (SLN) combustor
  - Gel rocket motor rig
- **Future work - demo testing**

Technical Merit

- Many industrial and manufacturing process sensors have limited accuracy in applications involving high temperatures and/or pressures because they require extractive sampling.
- Extractive sampling introduces the unwanted effects of alterations in temperature and chemical composition as well as slow response times.
- Sampling also frequently requires that costly maintenance schedules be put in place.
- A multichannel TDLAS affords a direct, rapid, and quantitative measure of the species concentration and temperature along a line in the probed region.
- Using fiber optics, the system is easily expanded to probe several locations simultaneously.
- Using NIR laser sources leverages “inexpensive” telecom technology and eliminates the need for cryogenic cooling.
- Passive physical probes cannot withstand the combustion environment (at least not for very long!)

Example

- **Thermometry**
  - Need: a non-intrusive high temperature sensor for industrial app’s.
  - Problem: combustion temperatures frequently top 2000 K/3200^{o}F, exceeding thermocouple limits;
  - Thermocouple shortcomings: intrusive, fragile, time lag, radiation error, conduction error,...

Thermocouple failing near 2000 K in methane - air flat flame burner

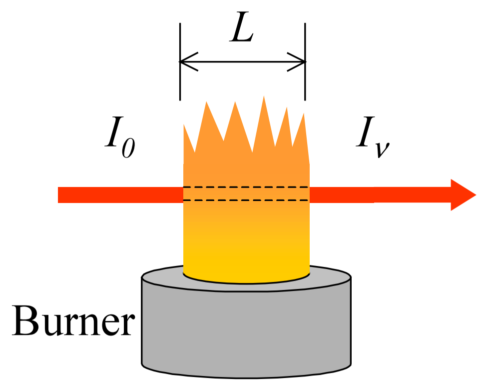
  - Solution: non-intrusive TDLAS targeting water vapor

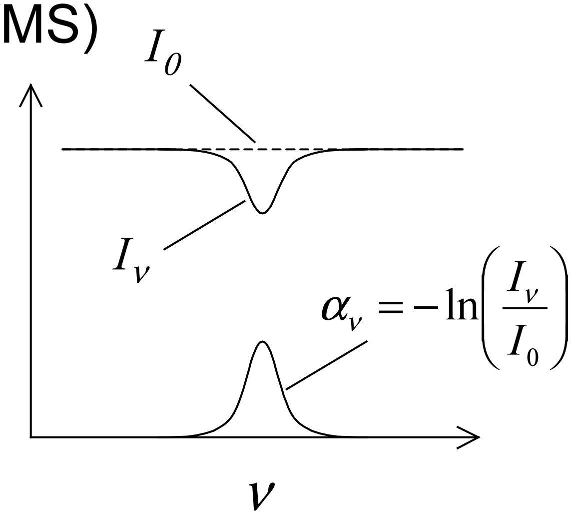
Approach/background - mole fraction

- **Scanned wavelength absorption measurement**
  - 1. Direct absorbance
  - 2. Wavelength modulation spectroscopy (WMS)

Beer-Lambert relation:

$$\frac{I_\nu}{I_0} = e^{-\alpha_\nu}$$





For line j of species i:

$$\text{Absorbance} = \alpha_\nu = P_i X_i S_j \phi_j L$$

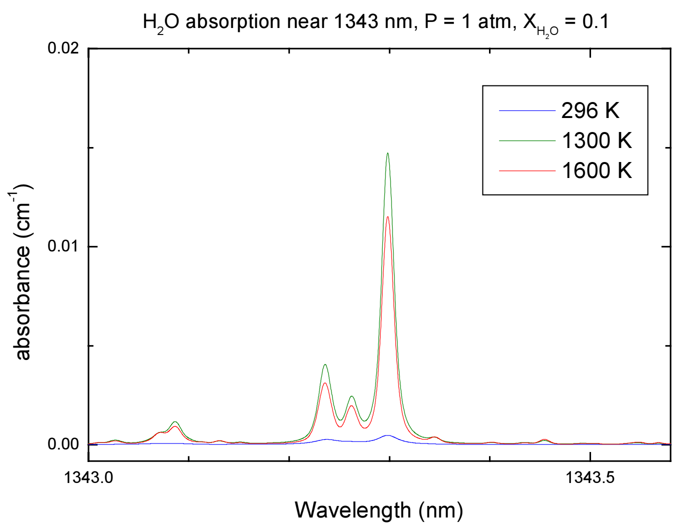
Where:

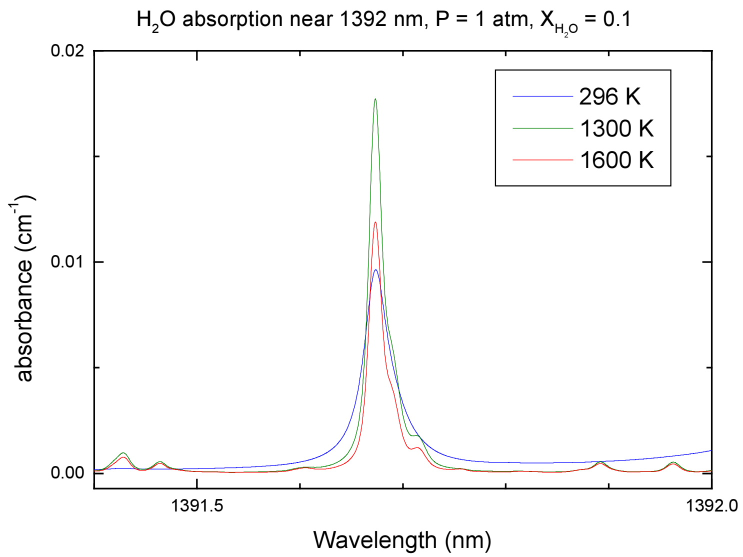
$$S_j = S_j(T)$$

$$\phi_j = \phi_j(\nu)$$

Measured $\alpha_{\nu,\text{peak}}$ yields X_i from: $$X_i = \frac{\alpha_{\nu,peak}}{P S_j \phi_j L}$$

Approach/background - temperature





Ratio of peak absorbances:

$$R_{peak} = \frac{(\alpha_{\nu,1})_{peak}}{(\alpha_{\nu,2})_{peak}} = \frac{S_1(T_0)\phi_1}{S_2(T_0)\phi_2} \exp\left[-\frac{hc}{k}(E_1"-E_2")\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]$$

Measured R_{peak} is sensitive primarily to T only.

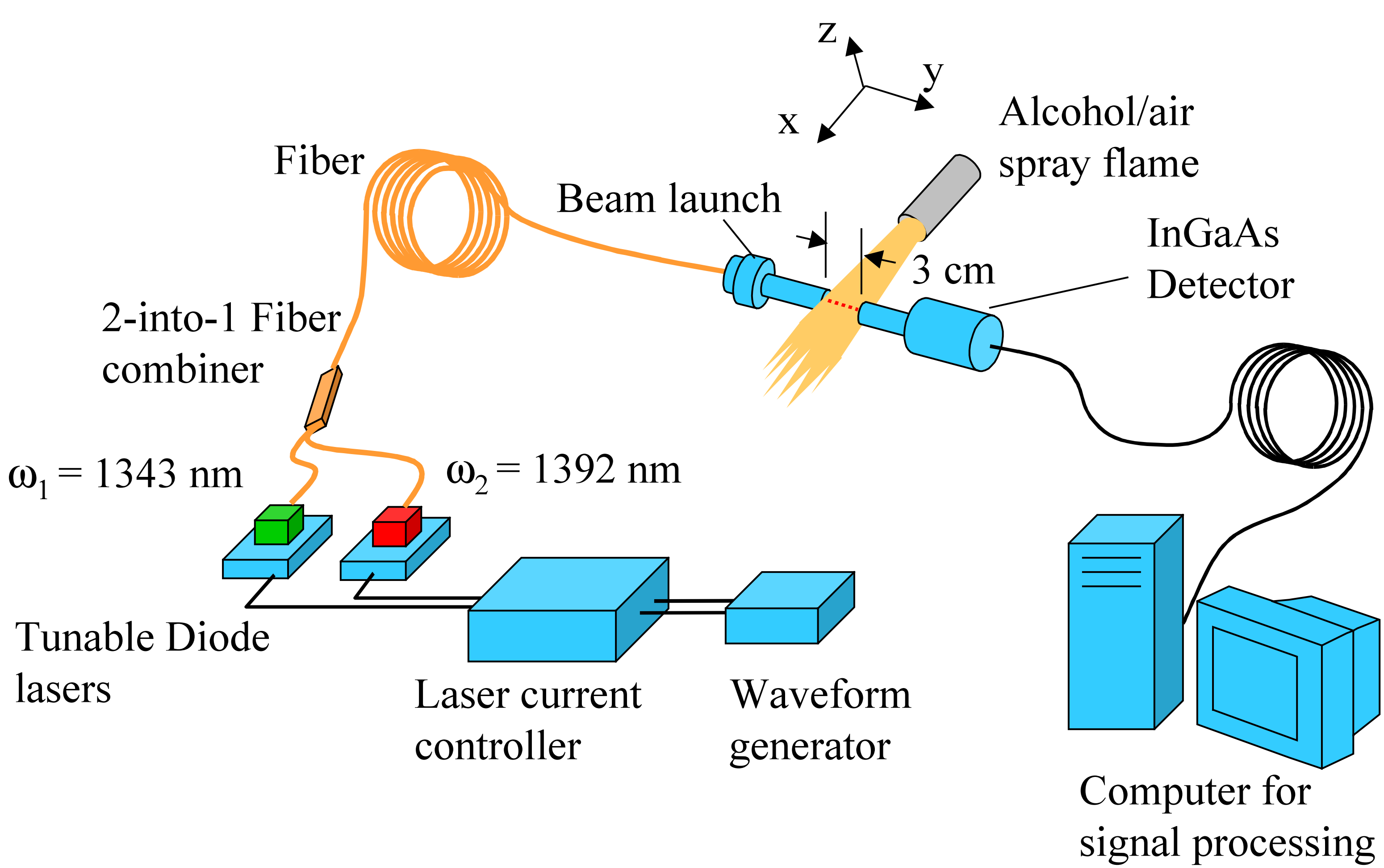
Technical Progress and Outlook

- **Major progress/accomplishments to date**
  - ***Modeled and validated high temperature spectra***
  - ***Built several prototypes***
  - ***Tested WMS and direct absorbance strategies***
  - ***Identified new temperature measurement strategies***
  - ***Demonstrated temperature/mole fraction sensing in turbulent combustion***
  - ***Compared measurements with thermocouples/calculations***
  - ***Demonstrated simultaneous multiple temperature sensing locations***
  - ***Demonstrated simultaneous temperature/multiple species mole fraction measurement***
  - ***Made preliminary comparison to chemiluminescence data***

Phase II Test Environments

- **Torch for combustion chemical vapor deposition (CCVD) of coatings**
  - simultaneous thermometry/H_2O mole fraction
  - tomographic profiling
- **Staged low-NOx (SLN) combustor**
  - simultaneous thermometry at multiple locations
  - comparison with chemiluminescence
- **Gel rocket motor component test (pending)**
  - simultaneous thermometry/multiple species mole fraction

CCVD Torch Application: 2-laser H_2O

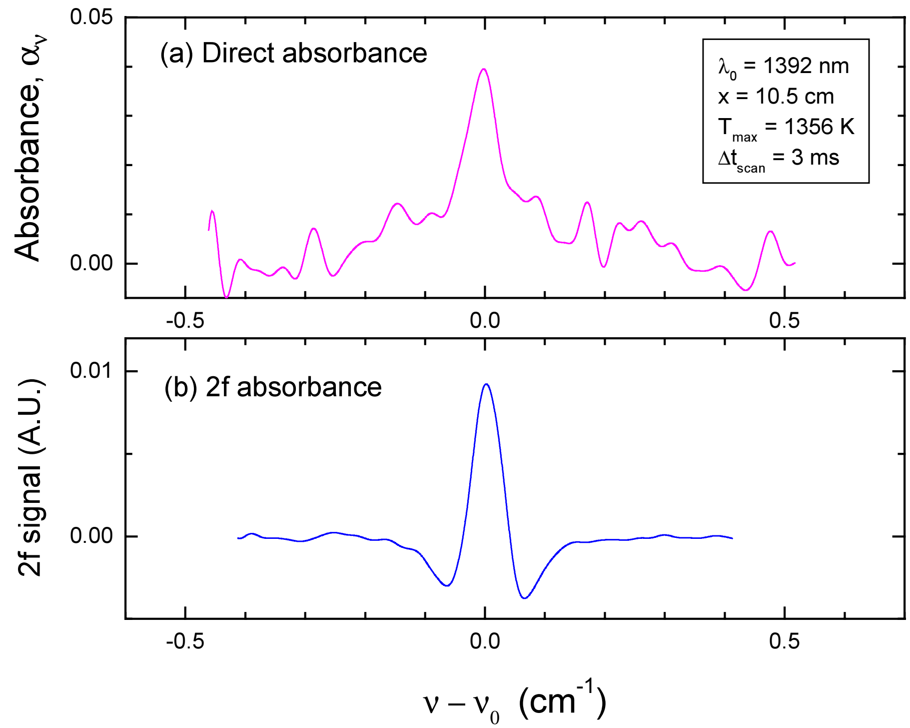


CCVD Torch: strategy for turbulence

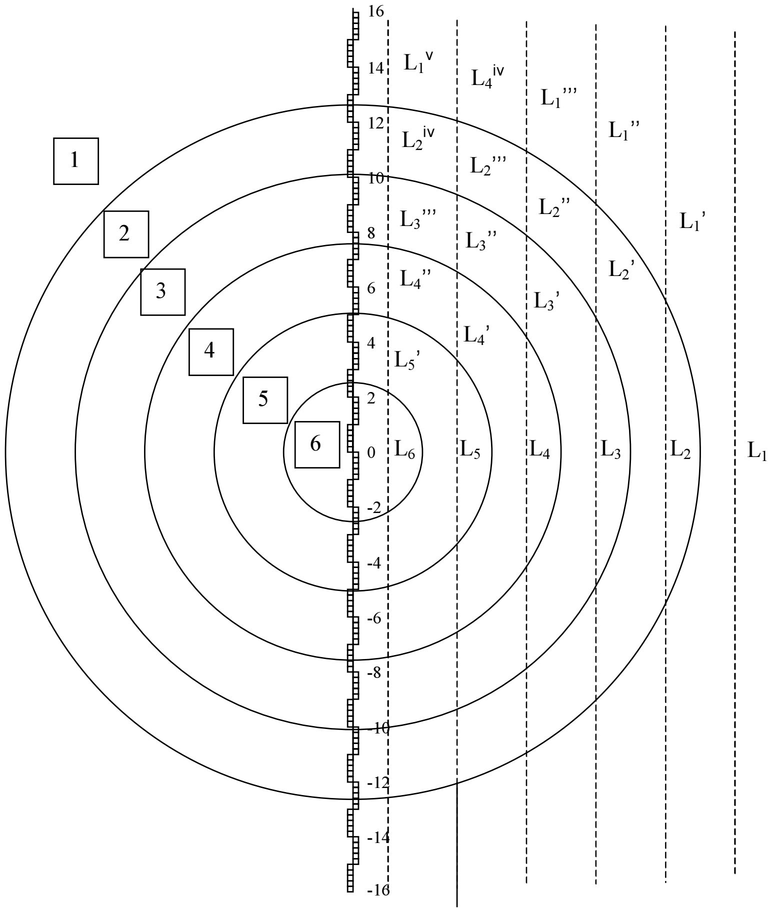
Compared direct absorbance to WMS:

Direct absorbance lineshape perturbed by noise; S/N ~ 3

2*f* lineshape less noisy and has zero baseline; S/N ~ 35



CCVD Torch: *"onion peeling" tomography*



For $i > 1$:

$$L_i = 2\sqrt{r_i^2 - (r_i - \Delta x/2)^2}$$

$$L_i' = 2\sqrt{r_i^2 - (r_i - 3\Delta x/2)^2} - L_{i+1}$$

$$L_i'' = 2\sqrt{r_i^2 - (r_i - 5\Delta x/2)^2} - L_{i+1}' - L_{i+2}$$

$$L_i''' = 2\sqrt{r_i^2 - (r_i - 7\Delta x/2)^2} - L_{i+1}'' - L_{i+2}' - L_{i+3}$$

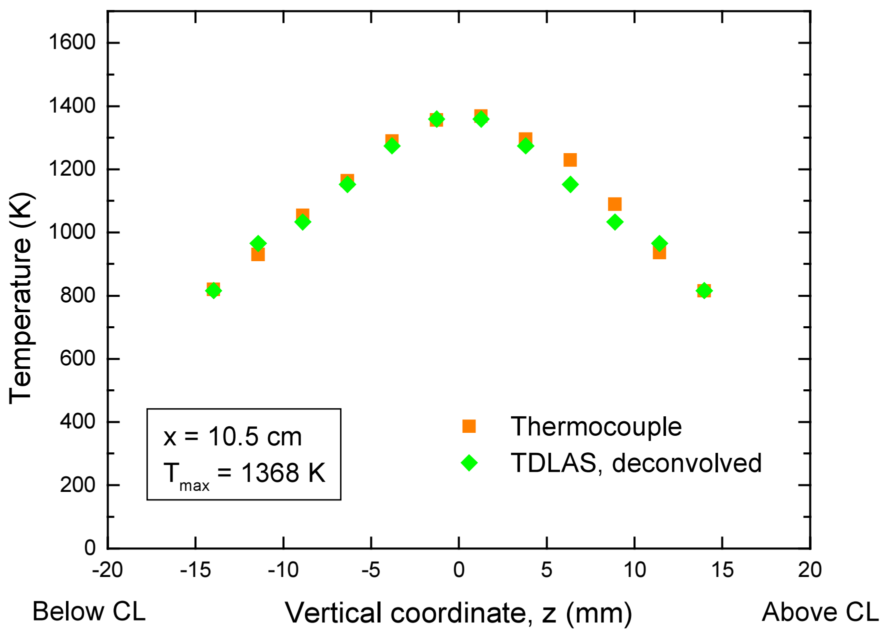
$$L_i^{\mathrm{iv}} = 2\sqrt{r_i^2 - (r_i - 9\Delta x/2)^2} - L_{i+1}''' - L_{i+2}'' - L_{i+3}' - L_{i+4}$$

$$L_i^{\mathrm{v}} = L_i - L_{i+1}^{\mathrm{iv}} - L_{i+2}''' - L_{i+3}'' - L_{i+4}' - L_{i+5}$$

- **The path length of each segment is calculated from the geometry.**
- **Starting with the outermost ring, a/L is calculated for each region.**

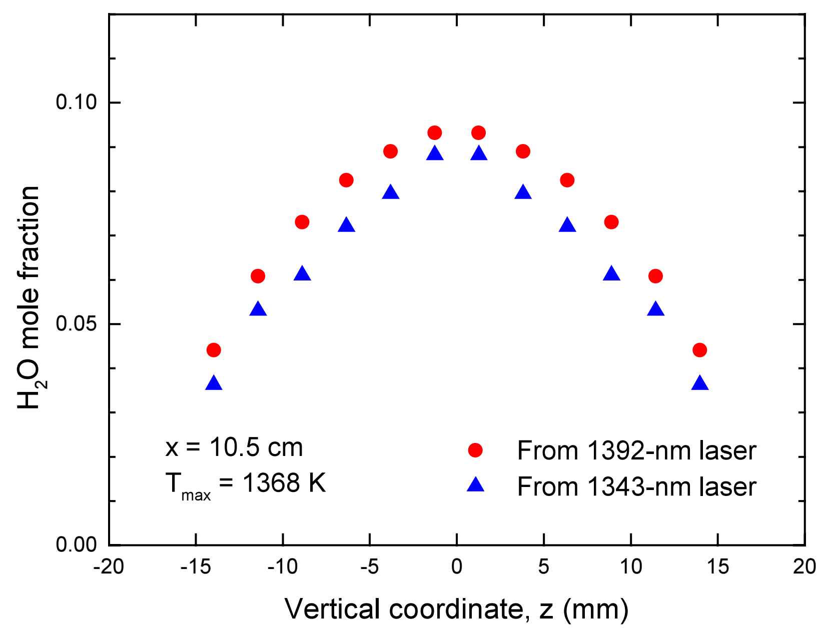
CCVD Torch Results

Temperature profile:



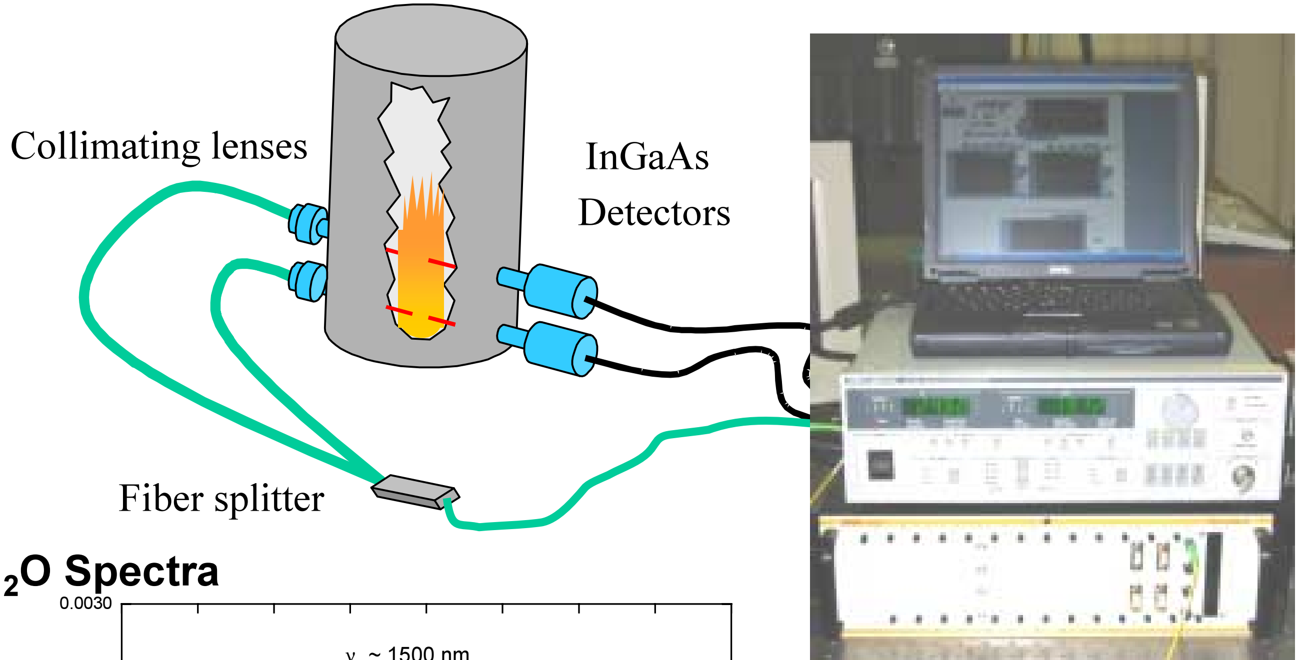
Excellent agreement
(up until thermocouple failure)

H_2O mole fraction profile:

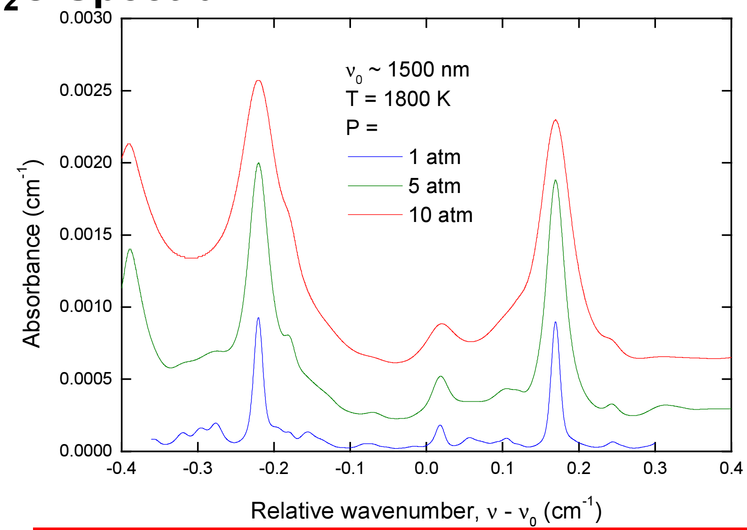


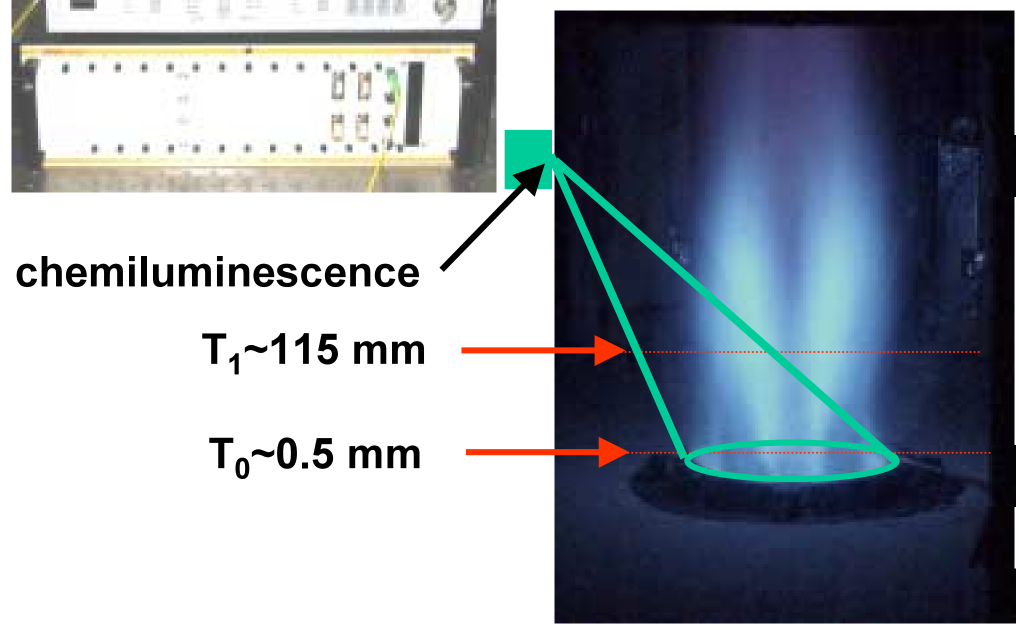
Two lines agree within 10%
(some discrepancy at locations closer to nozzle)

SLN Combustor: multiple probe direct absorbance with single laser TDLAS

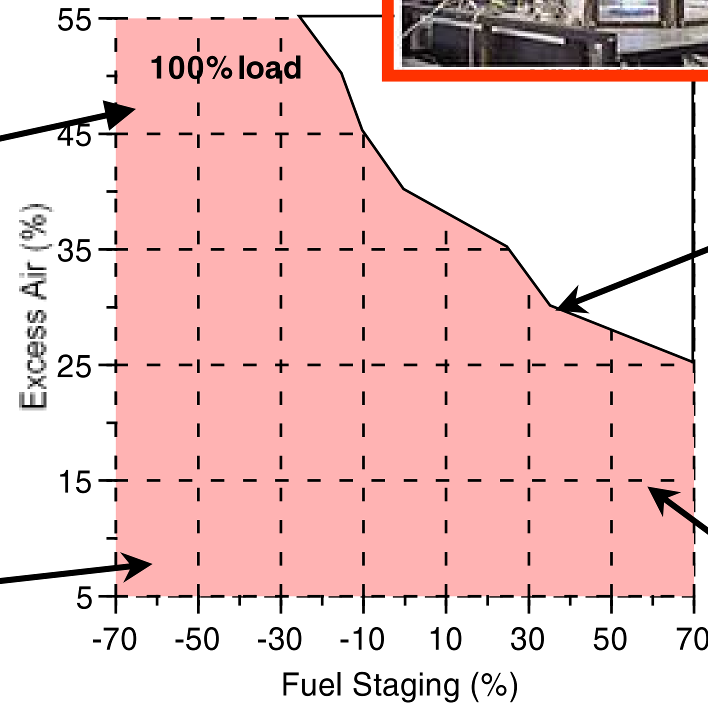


H_2O Spectra



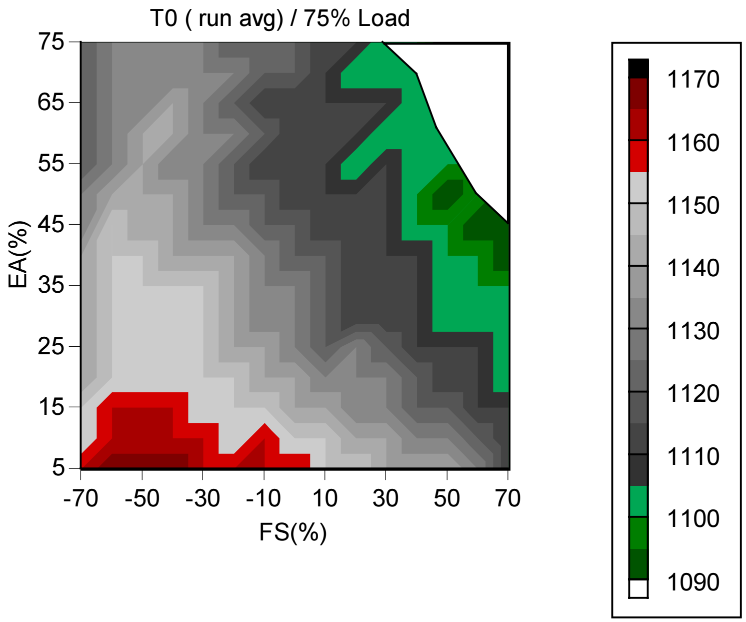


SLN Stability Map

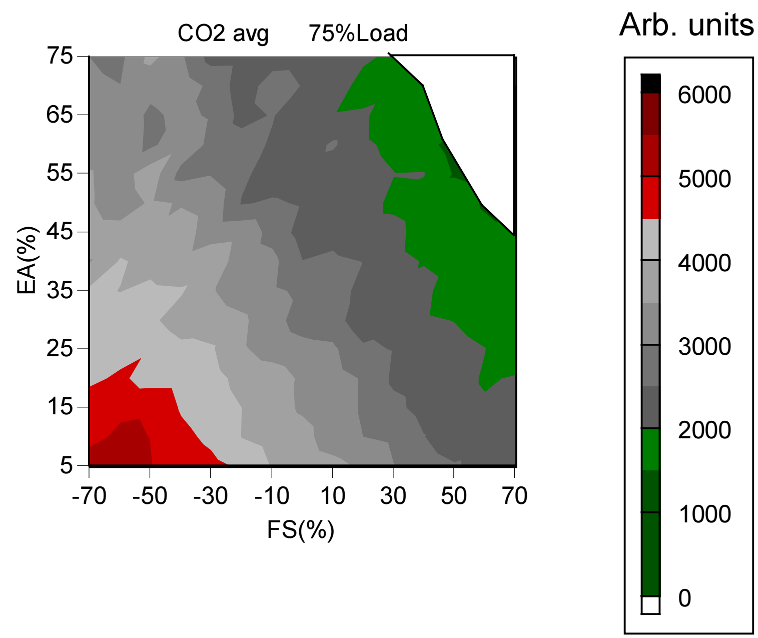


SLN Combustor Results - T0 position

TDLAS temperature:



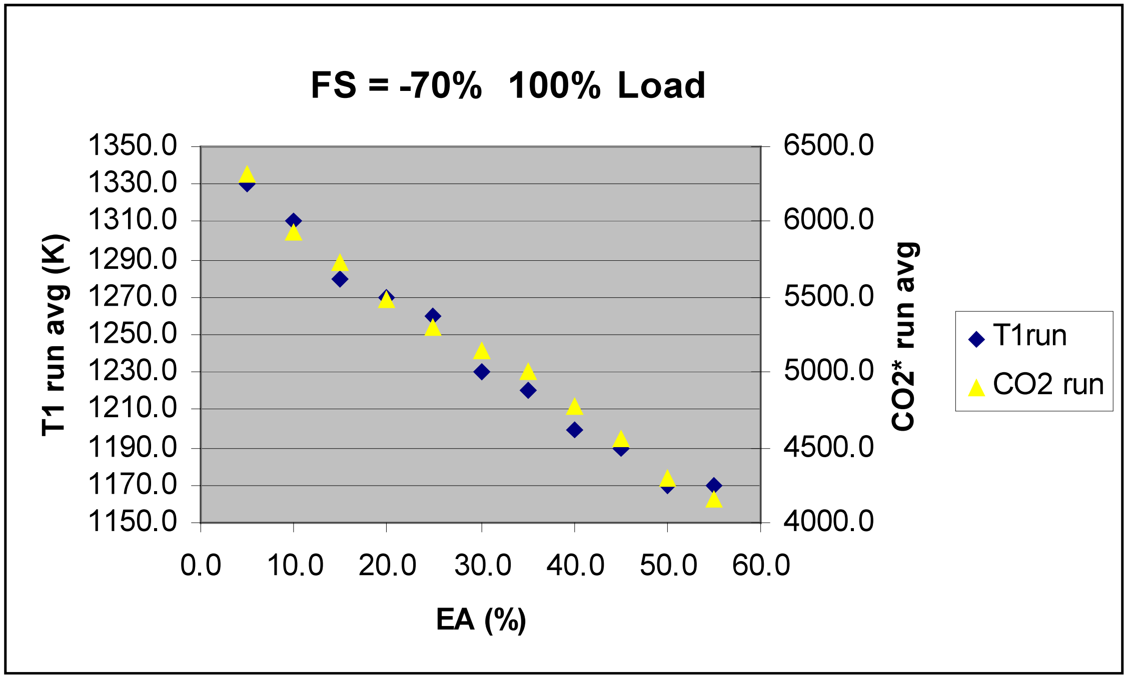
CO_2 chemiluminescence:



FS = fuel split: premix behavior < 0 < diffusion flame behavior

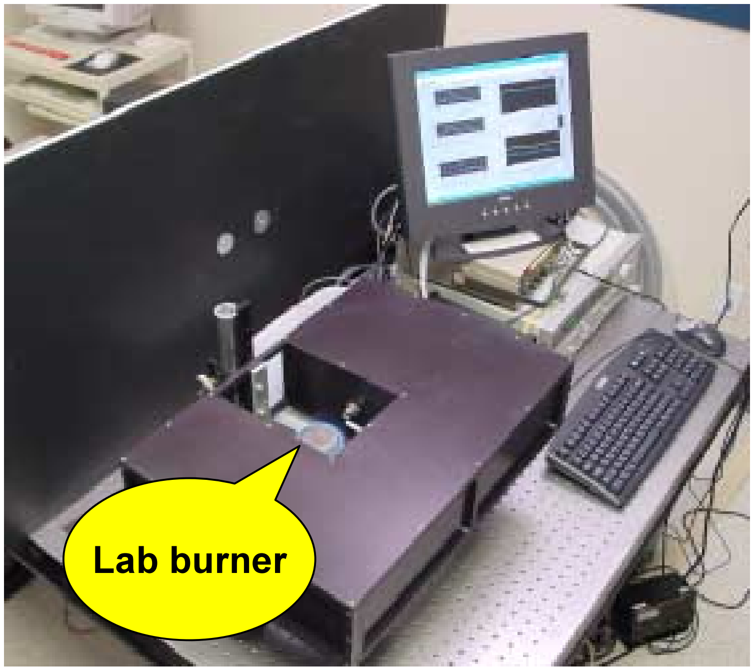
SLN Combustor Results - T1 position

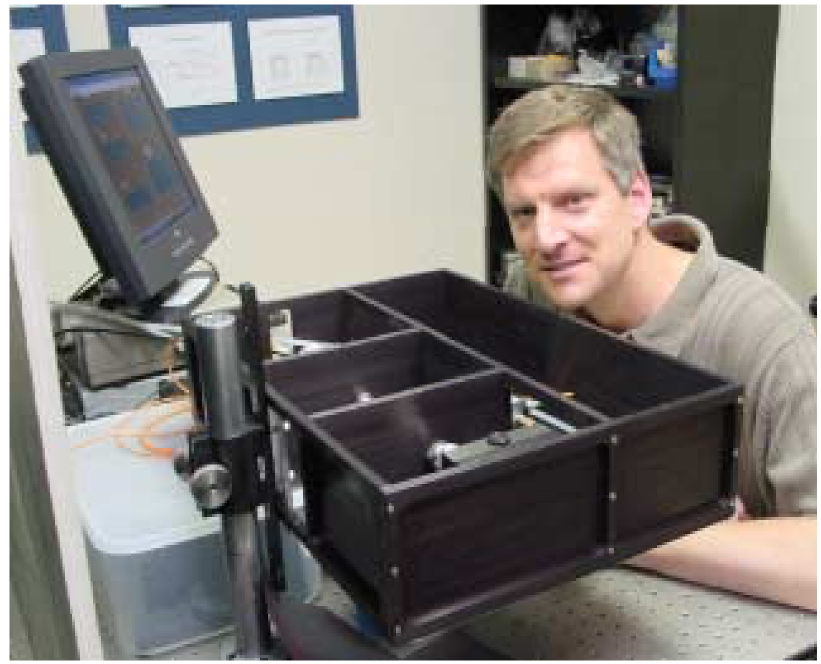
TDLAS temperature and CO_2 chemiluminescence:



EA = excess air: air beyond stoichiometric

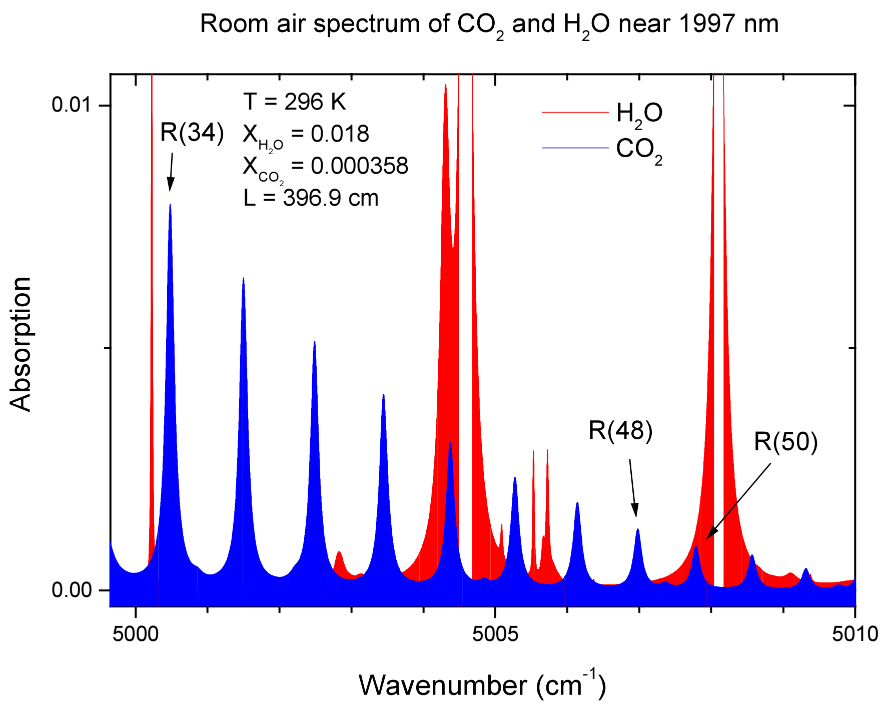
Gel Rocket Motor Prototype

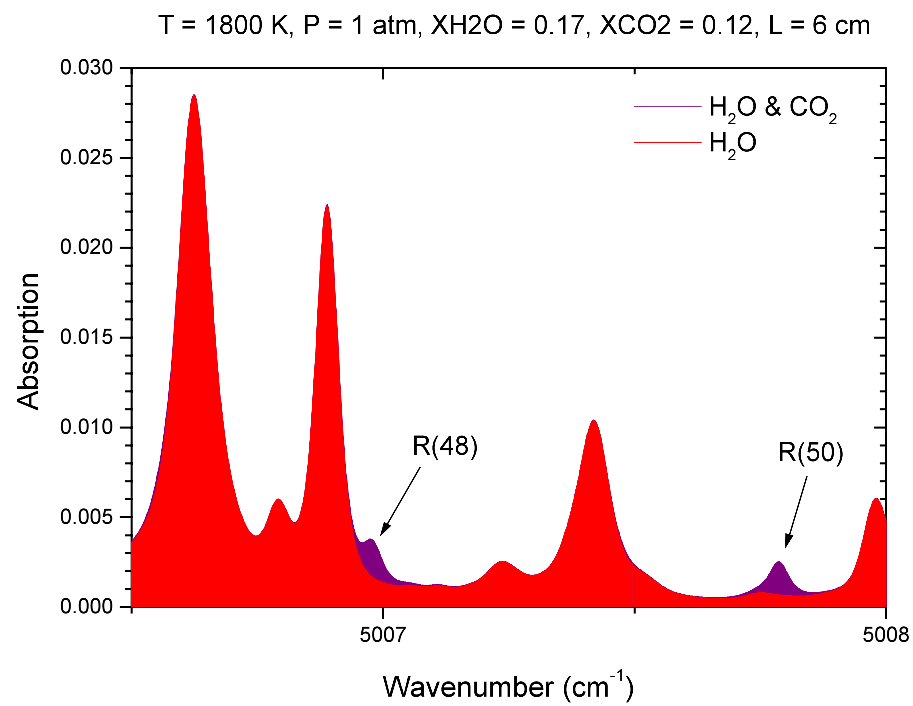




Measurement requirements:
pathlength ~ 1 in → Short pathlength dictated choice of alternative H_2O line pair
temperature ~ 1600 K
mole fraction H_2O ~ 47%
mole fraction CO_2 ~ 9% → CO_2 barely reachable with 1997 nm laser
time response ~ 50 μs

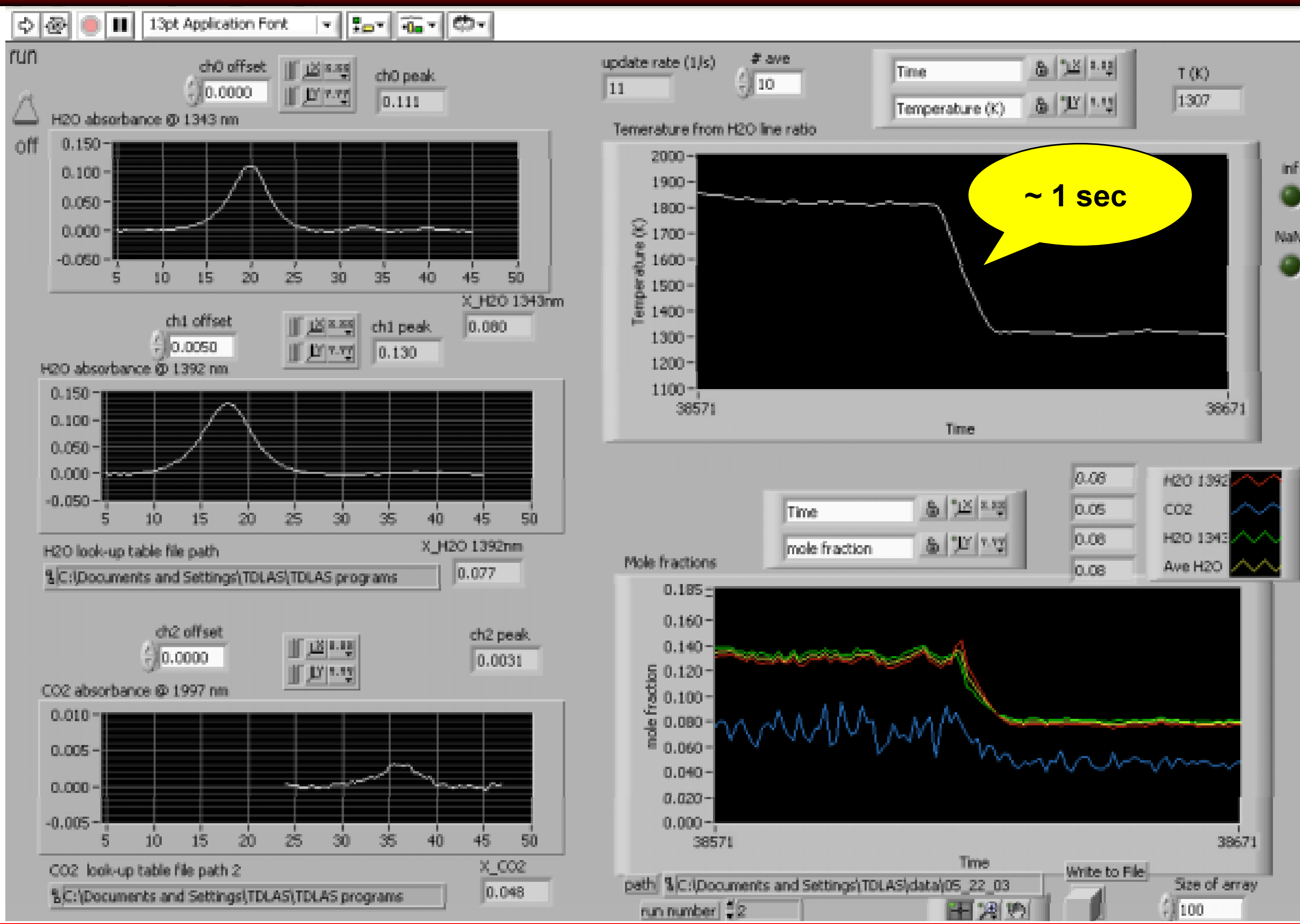
Gel Rocket Motor: CO_2 Spectra





- Ambient levels of CO_2 ~ 0.035%
- CO_2 level in a breath of air ~ 4%

Gel Rocket Motor: lab burner tests



Technical Progress and Outlook

- **Expected progress toward milestones/goals**
  - ***solid results with Phase II prototype expected to continue***
    - ***next test - 1.5 MW boiler***
    - ***active feedback control on CCVD torch***
    - ***temperature + CO_2 in gel rocket motor exhaust***
  - ***Real World Demonstration - where???***

- **Possible barriers**
  - **$**
  - ***Demonstration facility identification***

Technical Progress and Outlook

Conservative* Measurement Estimates

Species	Wavelength (nm)	minimum detectability with SNR = 10 (ppm)	Temperature range (K)
H_2O	~1480	600	900 to 3500
CO_2	~1997	60	600 to 2000
CO	~1560	1900	400 to 2000
Temperature	1500	50 K	900 to 3500

***** If we were to install the prototype in your facility tomorrow***

Technical Progress and Outlook

- **Industrial end-user involvement - *CCVD application***
  - 1 w on-site demonstration with Phase II prototype
    - T. Jenkins, P. DeBarber, and M. Oljaca, "Diode Laser Sensor for H_2O and Temperature Applied to Measurements in an Industrial Combustion Vapor Deposition Torch," 3rd Joint Meeting of the U.S. Sections of the Combustion Institute, Chicago, IL, March 16 - 19, 2003.
    - T. Jenkins, P. DeBarber, and M. Oljaca, "A Rugged Low Cost Diode Laser Sensor for H_2O and Temperature Applied to Measurements in a Spray Flame,"AIAA Paper No. 03-0585, American Institute of Aeronautics and Astronautics, 41st Aerospace Sciences Meeting and Exhibit, Reno, NV, January 6 - 9, 2003.
  - Planned 2nd visit - feedback control demo, summer 2003
  - Build Phase III systems - late fall 2003
    - integrate into production torch assemblies - early 2004
    - jointly market as part of CCVD package - begin late 2003

Technical Progress and Outlook

- **Univ. end-user involvement - *SLN 115 kW combustor***
  - Several w on-site demonstrations with Phase II prototype
    - T. P. Jenkins, P. A. DeBarber, Jinyang Shen, and V. G. McDonnell, "Diode Laser Sensor for Temperature and H_2O Measurements in High Pressure Environments," submitted American Institute of Aeronautics and Astronautics, 42nd Aerospace Sciences Meeting and Exhibit, Reno, NV, January 5 - 8, 2004.
    - T.P. Jenkins, E. Scott, P.A. DeBarber, V. McDonell, and T. DeMayo, "A Rugged, Low-cost Diode Laser Sensor for H_2O and Temperature," ISA Paper No. 4005, the Instrumentation, Systems, and Automation Society 48th International Instrumentation Symposium, San Diego, CA, May 5 - 9, 2002.
    - T. P. Jenkins, P.A. DeBarber, E. H. Scott, T. Demayo, V.G. McDonell, "Application of a Rugged, Low-Cost Diode Laser Sensor for H_2O and Temperature to a Model Industrial Boiler," Paper No. 043, Spring Meeting of the Western State Section of the Combustion Institute, San Diego, CA, March 25 - 26, 2002.
  - Planned testing on 1.5 MW boiler - late summer 2003

Technical Progress and Outlook

- **Industrial end-user involvement - *gel rocket motor***
  - Built a 2nd Phase II prototype
  - 1 w tutoring end-user at MetroLaser
  - Scheduled 1 week installation and testing mid-summer 2003

  - Phase III commercialization discussions
    - joint publications and exhibits - e.g., AIAA Reno 2004

Summary

- ***Multichannel TDLAS for Combustion Applications***
- A multichannel tunable diode laser spectroscopy system (TDLAS) affords a direct, rapid, and quantitative measure of the species concentration and temperature along a line in the probed region.
- Using fiber optics, the system is easily expanded to probe several locations simultaneously.
- The present system is being designed to simultaneously measure the concentrations of H_2O, CO_2, and CO as well as temperature.
- This is a four-channel system employing multiple diode lasers mated to a single fiber optic transmitter. Each laser diode is wavelength modulated.
- On the receiver end is a detector employing demultiplexing electronics to discriminate the four separate channels.
- The system software displays species concentration and temperature on the 100 ms timescale.

Acknowledgements

- ***Gideon Varga - DOE Sensors and Automation***
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